Unidirectional collisions of vertical Bloch lines

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(Submitted 1 July 1993; resubmitted 6 October 1993)
Zh. Eksp. Teor. Fiz. **105**, 176–185 (January 1994)

The unidirectional collisions of vertical Bloch lines are studied. It is shown that depending on the domain wall velocity and the size of topological charges, adhesion, break-off in the forward direction, reflection and stepwise generation of new pairs of 2π vertical Bloch lines with topological charges of opposite sign are possible. All this was observed in iron garnet films with perpendicular anisotropy and found by numerical solution of the Slonczewski equations.

INTRODUCTION

Vertical Bloch Lines (VBL) are elements of the ferromagnet domain wall (DW) structure. They are Néel parts of Bloch domain walls and may have topological charges that are multiples of π. VBL provide an example of topological magnetic solitons far more general than domain walls. 2π VBL serve as bits of information in ultradense on-line storage systems.[1] Experimental studies of VBL dynamic properties are based on the currently known detection methods. The anisotropic dark-field diffraction technique[2] makes it possible to detect static VBL in uniaxial iron garnet films having a small quality factor Q. The technique is based on the variation of light reflection from DW microdeformations in a Bloch line. The high speed photography technique enables detection of dynamic VBL by solitary flexural DW waves accompanying the former and arising due to gyroscopic forces.[3] The double-and triple-exposure high-speed photography procedures allow one to investigate the velocities of VBL motion in real time,[4] and to begin to study VBL collisions. In Refs. 5 and 6, head-on collisions of VBL having topological charges equal in magnitude and opposite in sign were considered. It was found experimentally that depending on the DW velocity, four different results are possible: annihilation, partial restoration, complete restoration (soliton-like behavior), and an increase in VBL topological charges after collision. The first three effects were obtained by Zvezdin, Popkov and Yar from the Slonczewski equations by numerical simulation.[7] For the same DW velocity, the amplitudes and velocities of solitary waves depend on the VBL topological charge.[4] Therefore it is possible to observe the collisions of solitary waves having different amplitudes and moving in the same direction. It was inferred that in unidirectional motion the VBL behave like solitons.[8] Numerical calculations made by Kotova and Chetverikov[9] showed that the collision of two VBL moving in the same direction results in one VBL with a total topological charge. In the present paper we give the results of experiments on and numerical calculations of collisions of Bloch lines with different (in absolute value) topological charges moving in the same direction. We have found that in this case, depending on the DW velocity as well as on the magnitude of topological charges of colliding VBL and system parameters, various effects can be observed, such as adhesion of two VBL, soliton-like behavior, reflection of the pursuing VBL from the other (moving with smaller velocity), along with an increase in its topological charge, and generation of a sequence of new 2π VBL pairs with topological charges opposite in sign.

1. EXPERIMENTAL PROCEDURE

To study VBL collisions in real time, i.e., during one passage of the DW through the sample, we used triple-exposure high-speed photography technique[10] which is a refinement of the double-exposure high-speed photography method.[11] During one pulse of the magnetic field moving the DW and VBL, the sample is illuminated by three light pulses 8 ns long from three rhodamine dye lasers separated by definite time intervals. The contrasts of the domain structures obtained from the first and the last light beams were opposite. The region traversed by the DW in the delay time between the first and the third light pulses was registered as a dark band, as in the double-exposure method. The first DW dynamic position is registered as a light-to-dark transition, and the last one as a dark-to light transition. During this time interval the DW containing the VBL was illuminated by another light pulse which gave a phase contrast image of the DW as a narrow dark line. The intensity of transmitted light in the phase contrast is lower than in the domain contrast. Therefore the dark band obtained with the help of the first and third light pulses remains distinct, though the contrast becomes worse in comparison with the second light beam, which was not additionally brightened. Nevertheless, the contrast is much better than in the case when all three DW positions are photographed at a phase contrast for which each DW image falls within the region illuminated by the two other beams. Thus, the photographs registered three positions of the dynamic DW and solitary flexural waves accompanying moving VBL at different instants of time: before the collision, at the moment close to the collision or immediately after, and some time after the collision. The VBL velocities before the collision can be found from the distance between the first and the second VBL positions, while their velocities after the collision are found from the distance between the second and third positions.

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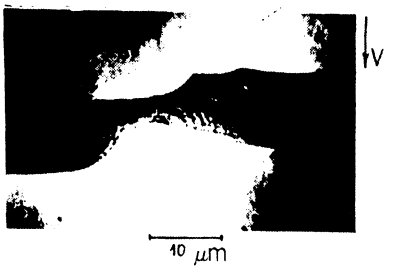

FIG. 1. Triple-exposure high-speed photograph of two-VBL adhesion after collision. The delay time between two light pulses is 0.3 μs.

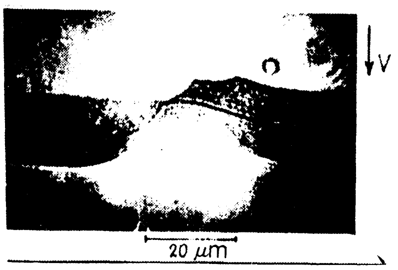

FIG. 3. High-speed triple exposure of the reflection of a pursuing VBL with lesser topological charge after collision with a VBL with greater topological charge.

To create two VBL with different topological charges on the DW, two current pulses of different amplitudes were fed into the current loop at some interval. The studies were conducted in an epitaxial film of iron garnet $(BiLaTm)_3(FeGa)_5O_{12}$ with domains 40 μm wide, $4\pi M_S = 100$ G, $Q=45$, and DW mobility $\mu = 280$ cm/s · Oe.

2. EXPERIMENTAL RESULTS

If the topological charges of Bloch lines are small and the DW velocity is far from the maximum and does not exceed 17 m/s, then the collision results in VBL "adhesion" (Fig. 1). The delay time between two successive light pulses is 0.3 μs. In the first (upper) position on the DW there are two VBL accompanied by solitary waves of different amplitudes. The asymmetry of the solitary wave form makes it possible to find the direction of VBL motion. Both VBL move in the same direction—from right to left. The VBL with the lesser charge, accompanied by the DW flexure solitary wave of lesser amplitude, is behind the other one. Bloch lines with a large topological charge move slower, so the VBL with the smaller topological charge catches up to the VBL with the larger topological charge. Upon collision, there remains only one VBL, which keeps moving in the same direction, more slowly than the VBL with the larger topological charge before the collision. Its topological charge equals the sum of the topological charges of the colliding Bloch lines. This result is consistent with the calculations in Ref. 9.

If VBL with large topological charges collide and theDW velocity is sufficiently large (in our experiment, at least 17 m/s), then in the case of unidirectional motion, it is possible, as in the case of head-on collisions, to observe soliton-like behavior of the VBL. The solitary waves of different amplitudes switch places when they collide, their initial velocities remaining unchanged. The VBL with the smaller topological charge moves ahead of the the other one. The triple exposure of this case is displayed in Fig. 2.

For DW velocities exceeding 25 m/s after the collision, reflection of the VBL with the lesser topological charge is possible (Fig. 3). Three positions of the DW and solitary waves on it separated by time intervals 0.3 μs long are seen there. Before the collision (the upper DW position in the figure), both VBL move in the same direction. The amplitude of the rear wave is smaller than that of the front wave, its velocity being accordingly larger. In the second position, the VBL with the lesser topological charge catches up with the VBL with the greater charge. After the collision (the lower DW position in the photograph), there are again two solitary flexural waves with different amplitudes accompanying two VBL. The larger one moves in the initial direction with a smaller velocity than before the collision. The VBL with the lesser topological charge moves in the opposite direction.

Upon further increase in the DW velocity (> 33 m/s), the collision may result in the generation of a sequence of new 2π pairs of VBL with opposite signs of their topological charges (Fig. 4). The first light pulse has registered the DW with two solitary waves on it. As in the previous cases,

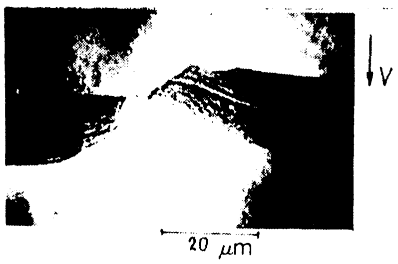

FIG. 2. High-speed triple exposure of collision of two VBL with topological charges of different size and the same sign. The VBL with the lesser topological charge breaks off and moves forward.

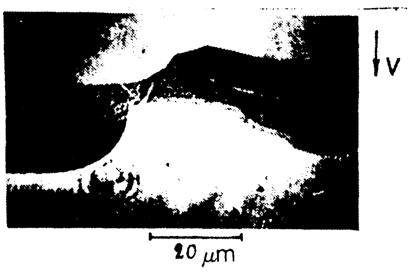

FIG. 4. High-speed triple exposure of the generation of a sequence of new 2π VBL pairs after the collision of two VBL with topological charges different in magnitude and the same in sign. The delay time between successive light pulses is 0.3 μs.

the solitary wave of lesser amplitude having larger velocity is behind, and the waves move in the same direction. The second pulse illuminates the DW some time after the line collision. Two VBL can be seen on the DW. The first is accompanied by a solitary flexural DW wave of large amplitude, its direction of motion remaining the same, its velocity becoming smaller and the topological charge larger. The second VBL accompanied by the solitary wave of small amplitude moves in the opposite direction. However, in contrast to the reflection case, in the third position there are already two solitary waves of small amplitudes corresponding to the 2π Bloch lines which move in the opposite direction. Each new 2π VBL pair is generated in 100 ns. Similar generation of 2π VBL pairs was observed in numerical simulations (Fig. 9).

In all the processes shown in Figs. 1–4, the sum of the VBL topological charges is conserved.

3. NUMERICAL CALCULATIONS AND COMPARISON WITH THE EXPERIMENT

We carried out numerical calculations of VBL collisions for unidirectional motion. As in Ref. 7, we used the Slonczewski equations:

$$-\varphi_{xx}+\tfrac{1}{2}\sin 2\varphi=\dot{q}-\alpha\dot{\varphi}-H_x\sin\varphi+v, \quad (1)$$

$$q_{xx}=\dot{\varphi}+\alpha\dot{q}+b^2 q, \quad (2)$$

where the functions q and φ correspond to the DW flexure normalized to the boundary thickness $\Delta_0=|A/K|^{1/2}$ and azimuthal angle of the magnetic moment. Here v is the normalized DW velocity, H_x is the field along the wall measured in the units of $8M_S$, α is the damping factor, A is the exchange rigidity constant, K is the constant of uniaxial anisotropy, x is normalized to $\Lambda_0=(A/2\pi M_S^2)^{1/2}$, time is normalized to $(4\pi\gamma M_S)^{-1}$, $b^2=\Delta_0 H_z'/4\pi M_S$, H_x' is the magnetic field gradient stabilizing the DW, and M_S is the saturation magnetization. The calculations were carried out for $\alpha=0.4$ and $b^2=10^{-4}$, which is fully consistent with the experimental values. In some of the calculations we put $b^2=5\cdot 10^{-3}$, which is close to the value usually used in numerical modeling.[7,9,12]

The initial conditions were chosen in the form

$$q(x,0)=0,$$
$$\varphi(x,0)=\sum_{i=1}^{i=N_1} 2\arctan\exp\frac{x-x_1-i\delta}{\Lambda_0}+\sum_{i=1}^{i=N_2} 2\arctan\exp\frac{x-x_2-i\delta}{\Lambda_0}, \quad (3)$$

where $\delta\simeq\Lambda_0$. As is seen from Eq. (2), the formation time of the DW flexure "tail" is $\tau_q=\alpha/b^2$. The formation time of the profile $\varphi(x,t)$ is much shorter. The numerical calculations showed that for $v=0.15$, the profile of 4π VBL is formed in 100 units of $(4\pi M_S\gamma)^{-1}$, that of 8π VBL in 300, and that of 20π VBL in 600 units.

It turned out that in the absence of the longitudinal field H_x over a wide velocity range ($v>0.15$), the VBL with sufficiently large charges form a very unstable Bloch line with charge N_1+N_2, if after the collision $N_1+N_2>14$; it decays very quickly into two lines. Even a small field ($H_x=0.03$) stabilizes the VBL formed by pursuit, and if $N_1+N_2<30$, the decay does not occur. However for a larger total charge of the colliding VBL, even in large fields H_x, the leading part of the resulting VBL, breaks off at moderate DW velocities.

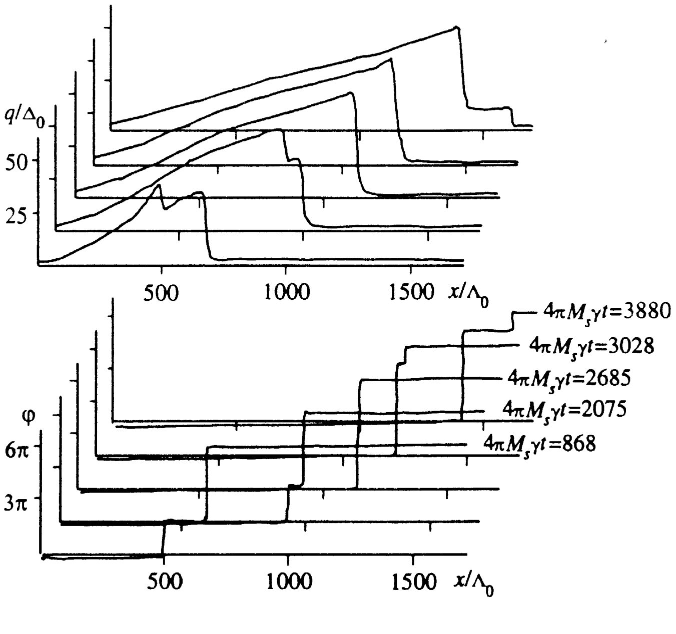

FIG. 5. Numerical solution of the Slonczewski equations at different times for two VBL with charges $N_1=2$ and $N_2=4$, for $H_x=0$, $b^2=10^{-4}$ and $v=0.4567$.

If the topological charges of Bloch lines are not very large, the break-off occurs only for sufficiently large velocities. For $N_1=2$ and $N_2=4$, 8, 12, and 20, we calculated the DW velocities for which VBL adhesion gives way to a π VBL break-off. These velocities are equal to 0.451, 0.397, 0.362, and 0.312, respectively.

The solutions of the Slonczewski equations for $N_1=2$, $N_2=4$, $v=0.4587$, and $H_x=0$ are shown in Fig. 5. After the collision, the first π VBL runs on ahead. In Fig. 6, the VBL velocities in the process of unidirectional collision of 2π and 4π lines are shown for $\varphi(x,t)=\pi/2, 3\pi/2,...,11\pi/2$.. For $t<2500$ (the first and second positions in Fig. 5), the VBL have velocities $u=0.35$ and $u=0.26$, respectively. For $t>3000$, i.e., after the collision (the fourth and fifth positions in Fig. 5), we obtain π and 5π VBL moving with velocities $u=0.44$ and $u=0.23$, respectively. The intermediate VBL (the third position in Fig. 5) looks like an ordinary Bloch line with a charge 6π which moves in a stationary regime, but with the help of Fig. 6 it is easy to see that different parts of the 6π VBL have different velocities, which leads to its decay.

The solution of the Slonczewski equations at different times is shown in Fig. 7 for $N_1=4$, $N_2=16$, $H_x=0.0314$, and $v=0.25$. It qualitatively corresponds to the experimental results displayed in Fig. 2. As a result of catching up, two VBL with charges 18π and 2π are formed.

For small charges N_1 and N_2, the DW velocity close to

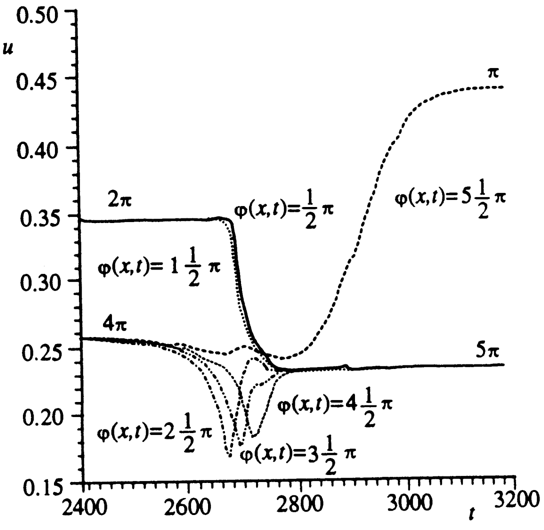

FIG. 6. Velocities $(dx/dt)_{\varphi(x,t)=\varphi_i}$ for $\varphi_i=\pi/2$, $3\pi/2,...,11\pi/2$ in the collision of 2π and 4π VBL.

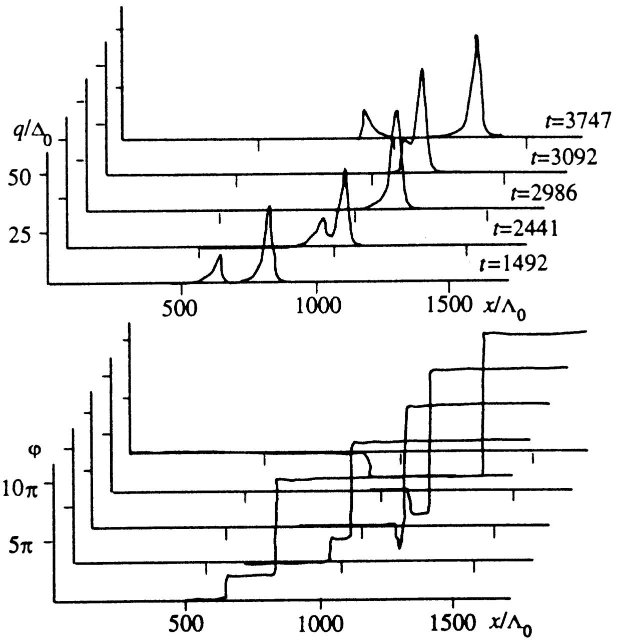

FIG. 8. Numerical solution of the Slonczewski equations for two VBL with charges $N_1=2$ and $N_2=8$, $v=0.3683$, $H_x=0.157$, and $b^2=5\cdot10^{-3}$. Upon collision, the 2π VBL coming up from behind is reflected.

critical, and relatively large stabilizing gradient ($b^2=5\cdot10^{-3}$) the numerical calculations illustrate the reflection of the pursuing VBL, as shown in Fig. 8. The velocity interval in which this process takes place is very narrow ($\Delta v\simeq0.01$), and depends on N_1 and N_2. This result qualitatively corresponds to the experimental result shown in Fig. 3. At higher velocities v, stepwise (in 2π) unbounded growth of the topological charges of the forward and reflected VBL occurs (Fig. 9). This result qualitatively corresponds to the experimental results shown in Fig. 4. For a small gradient ($b^2=10^{-4}$) and large velocities, the calculations yield only infinite stepwise VBL gen-

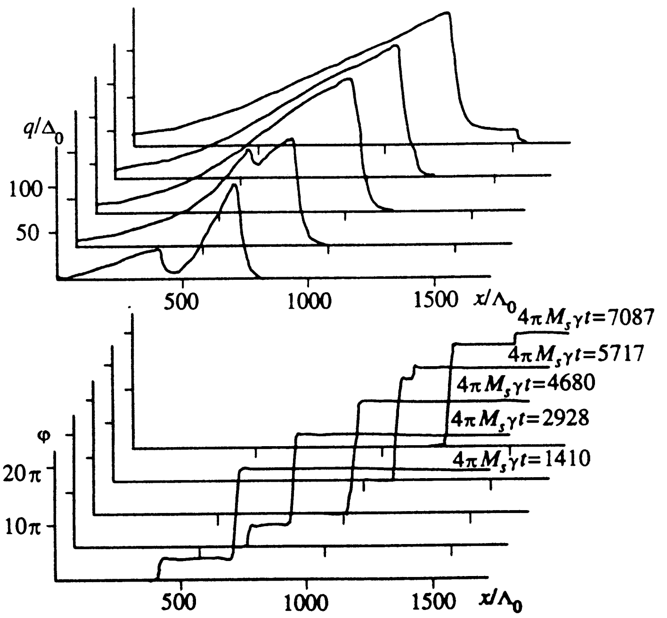

FIG. 7. Numerical solution of the Slonczewski equations at different times for two VBL with the charges $N_1=4$ and $N_2=16$, for $H_x=0.0314$, $v=0.25$, and $b^2=10^{-4}$.

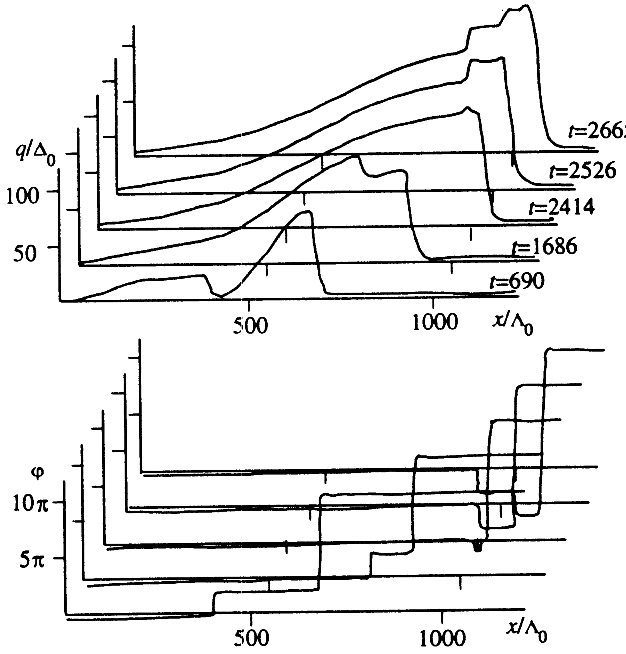

FIG. 9. Numerical solution of the Slonczewski equations for two VBL with charges $N_1=4$ and $N_2=16$, for $v=0.5972$ and $H_x=0.157$. Upon collision, an infinite generation of 2π VBL pairs sets in.

eration. If large VBL collide, the VBL which moves forward decays, and simultaneously the processes shown in Figs. 5 and 9 occur.

CONCLUSION

We have thus shown that in unidirectional VBL collisions, depending on the DW velocity and the size of topological charges, adhesion, break-off, reflection and stepwise generation of new 2π VBL pairs with topological charges opposite in sign are possible. All of these results were experimentally observed in iron garnet films with perpendicular anisotropy and found numerically from the Slonczewski equations. The processes considered may influence the function of memories which use VBL. The experimental results relating to head-on VBL collisions[6] are similar to those on fluxon collisions in distributed Josephson lines.[13] Experiments similar to those described above and involving the Josephson fluxons have not yet been carried out.

[1] S. Konishi, IEEE Trans. Magn. **19**, 1838 (1983).

[2] A. Thiaville, J. Ben Youssef, Y. Nakatani, and J. Miltag, J. Appl. Phys. **69**, 6090 (1991).

[3] T. M. Morris, J. G. Zimmer, and F. B. Humphrey, J. Appl. Phys. **47**, 721 (1976).

[4] M. V. Chetkin, V. B. Smirnov, A. F. Popkov *et al.*, Zh. Éksp. Teor. Fiz. **94**, 164 (1988) [Sov. Phys. JETP **67**, 2269 (1988)].

[5] M. V. Chetkin, I. V. Parygina, V. B. Smirnov, and S. N. Gadetskii, Zh. Éksp. Teor. Fiz. **96**, 337 (1990) [Sov. Phys. JETP **70**, 191 (1990)].

[6] M. V. Chetkin, I. V. Parygina, and L. L. Savchenko, IEEE Trans. Magn. **28**, 2350 (1992).

[7] A. K. Zvezdin, A. F. Popkov, and I. P. Yarema, Zh. Éksp. Teor. Fiz. **98**, 1070 (1990) [Sov. Phys. JETP **71**, 597 (1990)].

[8] M. V. Chetkin, I. V. Parygina, V. B. Smirnov *et al.*, JETP Lett. **49**, 204 (1989).

[9] E. E. Kotova and V. M. Chetverikov, Zh. Éksp. Teor. Fiz. **98**, 2011 (1990) [Sov. Phys. JETP **71**, 1131 (1990)].

[10] M. V. Chetkin, I. V. Parygina, and L. L. Savchenko, JETP Lett. **53**, 501 (1991).

[11] M. V. Chetkin, C. N. Gadetskii, A. P. Kuz'menko, and V. N. Filatov, Fiz. Tekh. Éksp. **3**, 196 (1984).

[12] A. K. Zvezdin, A. F. Popkov, and M. V. Chetkin, Usp. Phys. Nauk **162**, 151 (1992) [*sic*].

[13] K. Nakajima, H. Mizusawa, Y. Savada *et al.*, Phys. Rev. Lett. **65**, 1667 (1990).

Translated by E. Khmelnitski